

**NBSIR 77-1394**

# **A Computer Code for the Simulation of Turbulent Swirling Flow Through Closed-Conduit Flow Meters**

---

R. W. Davis and E. F. Moore

Fluid Meters Section  
Mechanics Division  
Institute for Basic Standards  
National Bureau of Standards  
Washington, D.C. 20234

December 1977

Final



---

**U.S. DEPARTMENT OF COMMERCE**

**NATIONAL BUREAU OF STANDARDS**



NBSIR 77-1394

**A COMPUTER CODE FOR THE  
SIMULATION OF TURBULENT  
SWIRLING FLOW THROUGH  
CLOSED-CONDUIT FLOW METERS**

R. W. Davis and E. F. Moore

Fluid Meters Section  
Mechanics Division  
Institute for Basic Standards  
National Bureau of Standards  
Washington, D.C. 20234

December 1977

Final

**U.S. DEPARTMENT OF COMMERCE, Juanita M. Kreps, *Secretary***

**Dr. Sidney Harman, *Under Secretary***

**Jordan J. Baruch, *Assistant Secretary for Science and Technology***

**NATIONAL BUREAU OF STANDARDS, Ernest Ambler, *Acting Director***



## ABSTRACT

A computer code is presented for the simulation of turbulent swirling flow through closed-conduit flow meters. The code is reasonably fast and accurate. The response of a flow meter to changes in its operating environment is easily assessed. Through the use of computer plotting routines, a complete picture of the flowfield through a meter can be obtained. An example flowfield for a target meter is presented.



## 1. INTRODUCTION

A computer code currently in use at NBS has proven highly useful in determining the characteristics of closed-conduit flow meters operating under realistic conditions [1]. This code, called TEACH, has been developed at the Department of Mechanical Engineering, Imperial College of Science and Technology, London, England. It is in wide use throughout the United States to model such turbulent flows as those found in combustors and in nuclear reactors [2, 3]. The TEACH code has generally been found to give reasonably accurate results within reasonable computing times. It was thus the logical candidate to pick in testing the feasibility of using turbulence modeling to study the flow through various types of closed-conduit flow meters. The results have demonstrated this feasibility, and computer simulation is now regarded as a vital tool in NBS' effort to improve flow metering practice.

The TEACH code can be used to obtain steady solutions for axisymmetric flows with or without swirl, a swirl subroutine having been added at NBS. The  $k\epsilon$ -model is employed to determine the turbulent shear stresses [4]. The resulting solution is in terms of velocities, pressure, and turbulence intensity. These can be computer plotted in such a way as to give a detailed view of the flowfield through a metering device. Changes in this flowfield due to variations in such parameters as upstream velocity profile, Reynolds number, or swirl number are easily assessed. A target meter flowfield is presented as an example.

## 2. BASIC EQUATIONS

The momentum and continuity equations for turbulent incompressible stationary flow employed in the  $k\epsilon$ -model are

$$\rho(\underline{q} \cdot \nabla)\underline{q} = -\nabla P - \nabla x[\mu_{eff}(\nabla x \underline{q})] \quad (1)$$

$$\nabla \cdot \underline{q} = 0 \quad (2)$$

in which  $\underline{q} = (U, V, W)$ , where  $U$ ,  $V$ , and  $W$  are the mean velocity components in the radial, axial, and tangential directions, respectively, in an axisymmetric cylindrical reference frame;  $P$  is the mean pressure;  $\rho$  is the constant density; and  $\mu_{\text{eff}}$  is the sum of the laminar and turbulent viscosities. The turbulent viscosity,  $\mu_t$ , is assumed to be a function of the turbulent kinetic energy,  $k$ , and dissipation rate,  $\epsilon$ , of  $k$ ; i.e.,

$$\mu_t = C_\mu \rho k^2 / \epsilon \quad (3)$$

where the empirical constant  $C_\mu$  is 0.09. The values of  $k$  and  $\epsilon$  are determined by the following transport equations written in axisymmetric cylindrical coordinates  $(r, z)$ :

$$\rho \left( V \frac{\partial k}{\partial z} + U \frac{\partial k}{\partial r} \right) = \frac{\partial}{\partial z} \left( \frac{\mu_{\text{eff}}}{\sigma_k} \frac{\partial k}{\partial z} \right) + \frac{1}{r} \frac{\partial}{\partial r} \left( \frac{r \mu_{\text{eff}}}{\sigma_k} \frac{\partial k}{\partial r} \right) + \mu_t G - C_D \rho \epsilon \quad (4)$$

$$\rho \left( V \frac{\partial \epsilon}{\partial z} + U \frac{\partial \epsilon}{\partial r} \right) = \frac{\partial}{\partial z} \left( \frac{\mu_{\text{eff}}}{\sigma_\epsilon} \frac{\partial \epsilon}{\partial z} \right) + \frac{1}{r} \frac{\partial}{\partial r} \left( \frac{r \mu_{\text{eff}}}{\sigma_\epsilon} \frac{\partial \epsilon}{\partial r} \right) +$$

$$C_1 \epsilon \frac{\mu_t}{k} G - C_2 \rho \frac{\epsilon^2}{k} \quad (5)$$

where the empirical constants are  $\sigma_k = 1.0$ ,  $\sigma_\epsilon = 1.3$ ,  $C_D = 1.0$ ,  $C_1 = 1.44$ , and  $C_2 = 1.92$ ; and  $G \equiv 2 \left[ \left( \frac{\partial U}{\partial r} \right)^2 + \left( \frac{U}{r} \right)^2 + \left( \frac{\partial V}{\partial z} \right)^2 \right] + \left[ \frac{\partial V}{\partial r} + \frac{\partial U}{\partial z} \right]^2 + \left( \frac{\partial W}{\partial z} \right)^2 + \left[ r \frac{\partial}{\partial r} \left( \frac{W}{r} \right) \right]^2$ . The origin of the values for the empirical constants is discussed in [4].

### 3. NUMERICAL SCHEME

The TEACH code employs the SIMPLE finite difference scheme. This scheme is described in [5, 6], while the code itself is discussed in [2, 7]. Only a brief review of TEACH will thus be given here.

The TEACH code employs a variably-spaced, rectangular grid. The radial cell dimension is only a function of radial position, and the axial cell dimension depends only on axial position. Normal velocities are specified along cell boundaries, and pressure, tangential velocity, turbulent kinetic energy, and dissipation rate are defined at cell centers. The system of equations (1) - (5) is finite differenced and solved iteratively by underrelaxation. The

nonlinear convective terms in these equations are differenced using a hybrid scheme comprised of central and conservative upwind differencing [8]. At each iterative step, the finite difference analogs of equation (1) are solved implicitly using a line-by-line procedure involving a tridiagonal matrix solver. The velocity field resulting from this solution of the momentum equations for a given iteration will probably not satisfy the continuity equation (2). Using this known (but probably incorrect) velocity field, equation (2) can be transformed into an equation for the pressure correction required to make the velocity field solenoidal. This pressure correction is calculated in the same implicit manner and is used to determine the final velocity field for a given iteration. These velocities are then used in the solution (by the usual implicit scheme) of equations (4) and (5) for  $k$  and  $\epsilon$ . Finally, equation (3) for  $\mu_t$  is updated and the next iteration begins. The iterations proceed until the sum of the absolute values of the residual mass and momentum sources is less than some preset small value. This summation is performed separately for the mass flow and each component of momentum, with the resulting sums to each be less than some small percentage of the mass flow and largest component of momentum, respectively, at the inlet to the computed region.

Boundary conditions must be specified at the inlet to the region of flow containing the metering device. The required conditions are radial distributions of  $U$ ,  $V$ ,  $W$ ,  $k$ , and  $\epsilon$ . The geometry of the flow meter itself is handled by not allowing fluid to cross the appropriate grid lines. The condition at the exit of the computed region is that axial gradients are zero. Shear stresses along walls are based on the logarithmic law; i.e., wall-function method of [4]. Axisymmetry is enforced at the centerline ( $r = 0$ ) of the computed section.

#### 4. COMPUTER PLOTTING

The plotting program makes extensive use of four CalComp (California Computer Products) subroutines. Three of these, PLOT, SYMBOL, and NUMBER, are part of CalComp's basic software package that adapts program output for plotting. The fourth subroutine, FLINE, is classified as a "functional" subroutine, in which basic subroutines are applied to more specified needs. Both basic and functional software is available from CalComp.

The PLOT subroutine converts the output data from TEACH (U, V, W, P, k,  $\epsilon$ ) into hardware codes for a pen plotter. SYMBOL enables printing of alphanumeric data, such as titles for plots. This subroutine also creates the symbols used to plot the data points. NUMBER is used to provide axis value labels on plots. The FLINE subroutine has the capability of plotting an entire array of data points with symbols, and then drawing straight lines or smooth curves between successive data points. A parabolic curve-fit is generally used at NBS.

The plotting program generally runs in less than three minutes and uses about 40K words of storage on the NBS UNIVAC 1108. About 1.5 hours is usually required to make the graphs from the resulting output. When a complete set of plots is generated, approximately 9 meters of 30 cm paper is used. Some examples of these plots for a target meter are presented in the next section.

#### 5. EXAMPLE: TARGET METER

As an example of what can be done with TEACH and the plotting program, a target meter flowfield is presented in Fig. 1. The target meter is merely a disc of zero thickness ( $T = 0$ ) suspended in the center of a circular pipe at a distance of four pipe radii from the inlet. The beta ratio (ratio of disc radius to pipe radius) is 0.5, and the Reynolds number based on pipe radius and mean inlet velocity is  $2 \cdot 10^5$ . The inlet conditions are based on fully-developed pipe

flow at this Reynolds number, with the axial velocity profile conforming to a standard 1/9-power law. A solid-body rotation is superimposed on these inlet conditions in order to assess the effects of swirl on the meter. The inlet swirl number, which represents the ratio of axial flux of angular momentum to axial flux of axial momentum, is 0.10. All quantities are nondimensional, with the characteristic length being pipe radius and the characteristic velocity being mean inlet velocity. There are 100 variably-spaced grid points axially and 20 variably-spaced ones radially. It required about 400 iterations to reach the final solution, which took about 40 minutes and 55K words of storage on the NBS UNIVAC 1108.

Figure (1a) shows pressure and axial velocity variations through the meter. The pressure difference across the disc can be integrated to give the force on the disc, which is related to flow rate. Figure (1b) gives wall shear stress ( $\tau$ ) and swirl number ( $S$ ) anywhere in the meter. Figure (1c) is a streakline (segmented streamline) plot, with each line segment being in the local flow direction at a given point. The recirculation zone along the pipe centerline behind the disc shows clearly, as does the concentration of grid points near the disc. Figure (1d) presents turbulence intensity based on local mean velocity,  $I$ , along the pipe wall and pipe centerline. The flattened peak along the centerline results from cutting off a spike which occurs at the end of the recirculation zone where the local mean velocity goes to zero ( $I \rightarrow \infty$ ). Figure (1e) shows axial velocity profiles at several critical points in the meter. Note the power-law inlet profile. The outlet profile has not yet returned to the fully-developed case. Figure (1f) presents tangential velocity profiles at the same locations as for the axial ones. The inlet profile is linear, denoting solid-body rotation.

## 6. CONCLUSION

The feasibility of performing computer simulations of turbulent swirling flow through closed-conduit flow meters has been demonstrated. A turbulence code, such as the TEACH code presented here, can, along with proper plotting routines, define entire flowfields quickly and cheaply. It is thus expected that this sort of simulation, in conjunction with well-chosen validation experiments, will become more common in the determination of the performance of flow meters and associated pipeline elements, such as upstream flow conditioners.

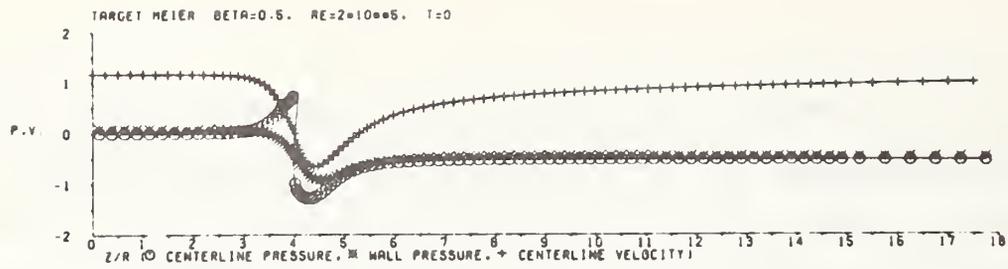
## 7. ACKNOWLEDGEMENT

The authors are grateful to Dr. G. E. Mattingly for his assistance and encouragement in the task of setting up these simulations at NBS.

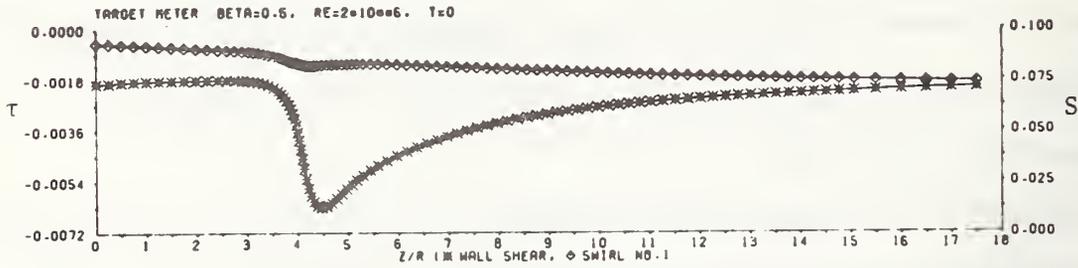
## 8. REFERENCES

1. Davis, R. W. and Mattingly, G. E., Numerical Modeling of Turbulent Flow through Thin Orifice Plates, Flow Measurement in Open Channels and Closed Conduits, ed. by Lafayette K. Irwin, National Bureau of Standards Special Publication 484, p. 491, October 1977.
2. Lilley, David G., Primitive Pressure-Velocity Code for the Computation of Strongly Swirling Flows, AIAA Journal, Vol. 14, p. 749, June 1976.
3. Chen, Yi Bin and Golay, Michael W., Coolant Mixing in the LMFBR Outlet Plenum, COO-2245-44TR, Dept. of Nuclear Energy, MIT, June 1977.
4. Launder, B. E. and Spalding, D. B., The Numerical Computation of Turbulent Flows, Comp. Meth. in Appl. Mech. and Eng., Vol. 3, p. 269, 1974.
5. Caretto, L. S., Gosman, A. D., Patankar, S. V., and Spalding, D. B., Two Calculation Procedures for Steady, Three-Dimensional Flows with Recirculation, Proc. Third Int. Conf. on Num. Meth. in Fluid Mech., ed. by Henri Cabannes and Roger Temam, Vol. II, Springer-Verlag, New York, p. 60, 1973.

6. Patankar, S. V., Numerical Prediction of Three-Dimensional Flows, Studies in Convection, Vol. 1, ed. by B. E. Launder, Academic Press, New York, p. 1, 1975.
7. Salimonu, Dauda O., Mathematical and Programming Details of the TEACH T and L Recirculating Flow Code, ANL-CT-76-22, Argonne National Laboratory, Oct. 1975.
8. Spalding, D. B., A Novel Finite Difference Formulation for Differential Expressions Involving Both First and Second Derivatives, Int. Journal for Num. Meth. in Eng., Vol. 4, p. 551, 1972.



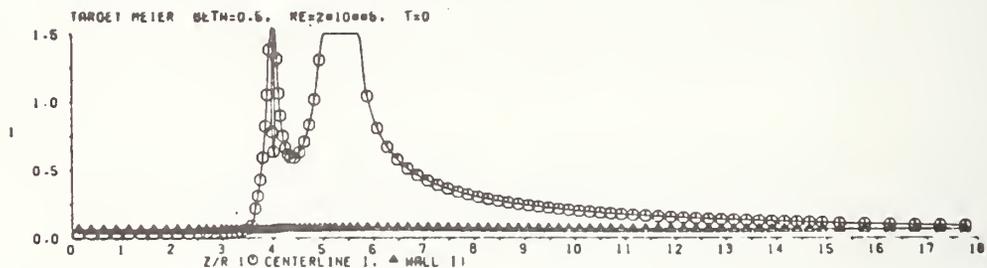
(a)



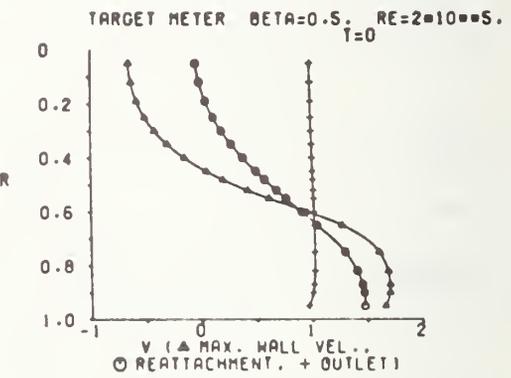
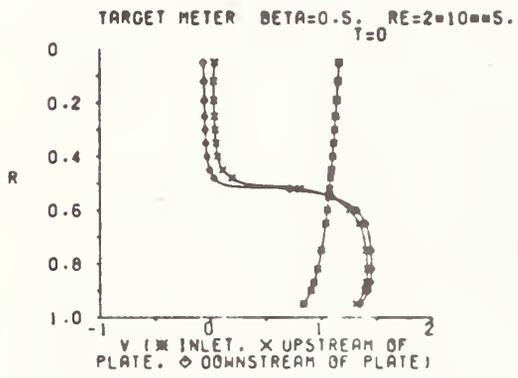
(b)



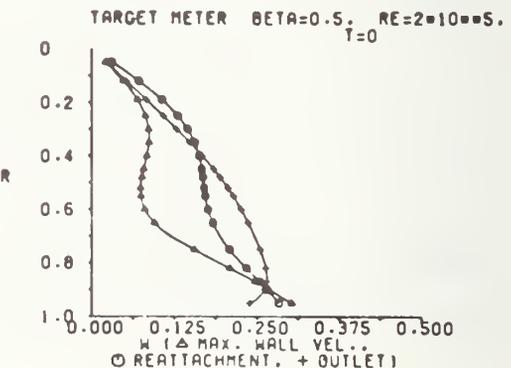
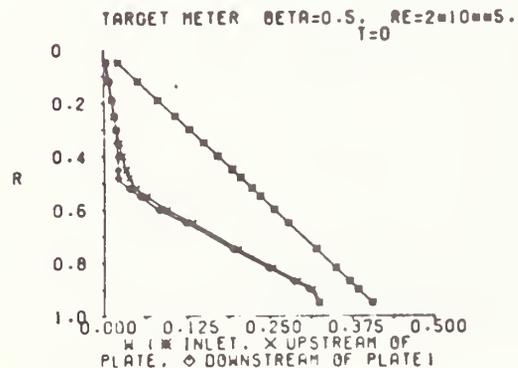
(c)



(d)



(e)



(f)

Fig. 1. Target meter flowfield.

U.S. DEPT. OF COMM. <b>BIBLIOGRAPHIC DATA SHEET</b>	1. PUBLICATION OR REPORT NO. NBSIR 77-1394	2. Gov't Accession No.	3. Recipient's Accession No.
TITLE AND SUBTITLE A COMPUTER CODE FOR THE SIMULATION OF TURBULENT SWIRLING FLOW THROUGH CLOSED-CONDUIT FLOW METERS		5. Publication Date December 1977 6. Performing Organization Code	
AUTHOR(S) R. W. Davis and E. F. Moore	8. Performing Organ. Report No.		
PERFORMING ORGANIZATION NAME AND ADDRESS NATIONAL BUREAU OF STANDARDS DEPARTMENT OF COMMERCE WASHINGTON, D.C. 20234		10. Project/Task/Work Unit No.	
2. Sponsoring Organization Name and Complete Address (Street, City, State, ZIP) National Bureau of Standards Department of Commerce Washington, D.C. 20234		11. Contract/Grant No.	
5. SUPPLEMENTARY NOTES		13. Type of Report & Period Covered Final	
5. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.) A computer code is presented for the simulation of turbulent swirling flow through closed-conduit flow meters. The code is reasonably fast and accurate. The response of a flow meter to changes in its operating environment is easily assessed. Through the use of computer plotting routines, a complete picture of the flowfield through a meter can be obtained. An example flowfield for a target meter is presented.		14. Sponsoring Agency Code	
7. KEY WORDS (six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons) Flow meter; meter performance; numerical modeling; turbulent flow.			
8. AVAILABILITY <input checked="" type="checkbox"/> Unlimited <input type="checkbox"/> For Official Distribution. Do Not Release to NTIS <input type="checkbox"/> Order From Sup. of Doc., U.S. Government Printing Office Washington, D.C. 20402, SD Cat. No. C13 <input checked="" type="checkbox"/> Order From National Technical Information Service (NTIS) Springfield, Virginia 22151	19. SECURITY CLASS (THIS REPORT) UNCLASSIFIED	21. NO. OF PAGES 10	
		20. SECURITY CLASS (THIS PAGE) UNCLASSIFIED	22. Price \$4.00

